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AN ANALYSIS OF GRAVITY AND GEODETIC CHANGES DUE TO RESERVOIR DEPLETION AT THE GEYSERS, NORTHERN CALIFORNIA

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ABSTRACT

In this paper gravity and geodetic data are combined with reservoir engineering studies to place upper and lower bounds on the volume and pore fluid mass changes within the depleted portion of the steam reservoir at The Geysers. We combined the gravity and temperature data to constrain the changes in pore fluid mass distribution due to fluid depletion, and thus limited the drainage volume to lie between 15 and 25 cubic km. We then modeled the surface geodetic data to determine values of strain between 3. and 8. X 10^{-5} for these drainage volumes. We determined that this strain could be induced either mechanically or thermally, and there is presently no way of distinguishing thermal from mechanical strain.

Since 1974, the average production rate at The Geysers steam field in Northern California (Figure 1) has been nearly 90 million kg of steam per day (Lippman and others, 1977). This large fluid withdrawal rate has caused changes in mass and volumetric strain within the depleted reservoir volume. From 1973 to 1977, time changes in pore pressure, surface strain (Lofgren, 1979), and gravity (Isherwood, 1977) occurred, while the reservoir temperature did not measurably change.

In this paper, the gravity and geodetic data from 1974 to 1977 are combined with reservoir engineering results (Weres, 1977) to determine the pore fluid deficit and strain within the drainage volume. Previously, (Isherwood, 1977; Hunt, 1977) it has been demonstrated that decreases in observed gravity with time reflect mass redistribution and deficits within some depletion volume. By comparing the total mass deficit measured from the gravity flux (found be integrating the gradient of the potential over some bounding surface) with the net mass produced, the recharge was estimated (Isherwood, 1977). Here we combine the gravity changes with well data to constrain the drainage volume between 15 and 25 cubic km. We then analyzed the geodetic data to determine the reservoir strain within the possible range of reservoir volumes. These concepts are summarized in Table 1.

At The Geysers, mapped values of maxima in subsidence, gravity change, pore pressure decline overlap. Figure 2 compares the decreases in observed gravity and pore pressure decay due to steam production. Isherwoods' (1977) previous analysis of this data determined that (1) the gravity changes were too large to be due solely to a deep water table below the producing zone penetrated by the wells, and (2) the gravity flux implied a mass deficit equal to the met mass produced, suggesting negligible recharge.

The lack of a measurable temperature change (plus or minus 3 degrees Celsius) limits the amount of water which has flashed to steam during production to less than 0.5% of the bulk rock volume. Yet reservoir engineering data imply that water flashes to steam to supply the fluid produced by the wells (Weres, 1977). Since the heat energy required in the phase transition from water to steam must come from the rock matrix, the lack of a measurable temperature change limits the change in reservoir liquid content due to steam production to that allowed by the error in the temperature measurements (Weres, 1977; Denlinger, 1979). The steam could come from a deep water table in this case, but this is inconsistent with the magnitude of the time changes in the gravity mentioned above.

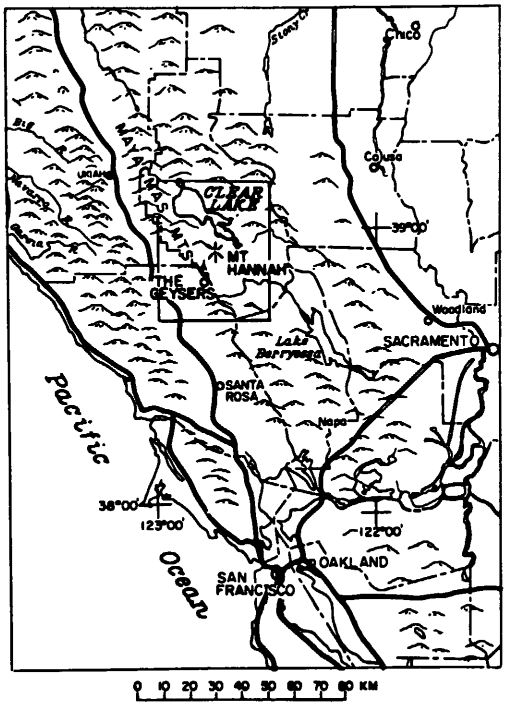


Figure 1. Index map, showing the region of discussion in this paper.

We modeled the gravity data using the thermal constraints above on the mass distribution. The maximum mass change due to water flashing to steam over the bulk reservoir volume, which is consistent with the lack of a measurable temperature change is .004 g/cc. Values of this magnitude were used to model the time changes in the gravity and the results are shown in Table 2. The value of .002 g/cc represents a lower bound in the modeling as the mass distribution is then too diffuse to reproduce the gravity amplitudes shown in Figure 2.

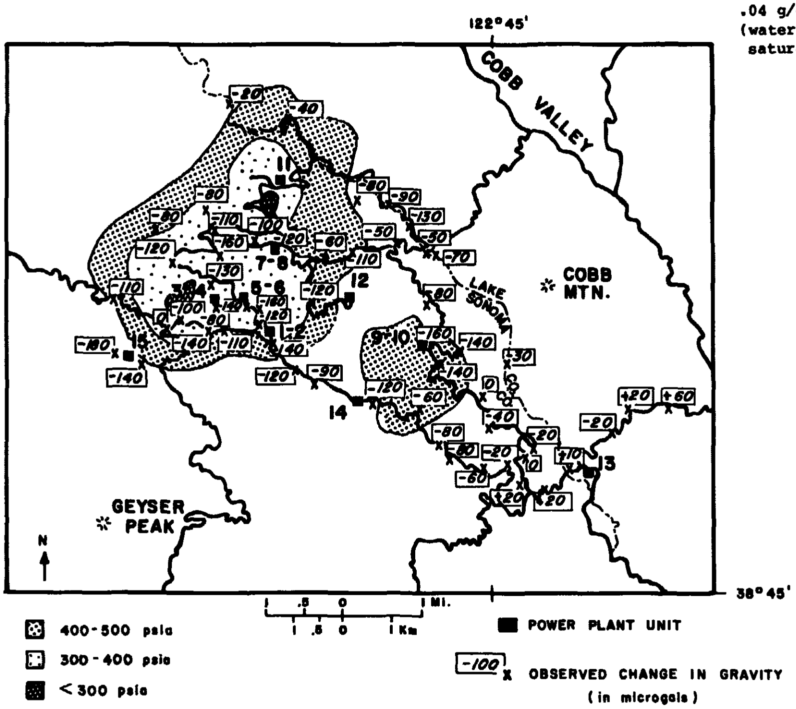


Figure 2. Time changes in surface gravity between 1974 and 1977 and the pore pressure decay near the top of the steam reservoir (from Lippman and others, 1977).

TABLE 1. A STUDY OF RESERVOIR DEPLETION AT THE GEYSERS GEOTHERMAL FIELD.

PHYSICAL CHANGES	SURFACE MEASUREMENT	RESULT OF ANALYSIS
Pore fluid mass deficiency due to production.	Change in gravity with time.	A tradeoff between a depleted reservoir volume and some uniform mass deficiency.
Volumetric strain within the reservoir.	Geodetic measurement of surface strain with time.	For uniform dilatation, a tradeoff occurs between volume and strain for a given maximum strain amplitude.
Change in temperature of reservoir during production, and change in enthalpy of produced steam.	Temperature and pressure measurements of steam within wells.	Limits on the pore fluid mass changes due to water flashing to steam within the reservoir volume.

TABLE 2. RESULTS FROM MODELING OF RESERVOIR GRAVITY CHANGE FOR A CYLINDRICAL VOLUME.

mass deficiency	radius	height	depth to top
.002 g/cc	1.8 km	3.7 km	0.0 km
	2.1 km	2.7 km	0.0 km
.003 g/cc	1.5 km	3.7 km	0.5 km
	1.7 km	2.7 km	0.5 km
.004 g/cc	1.8 km	3.7 km	1.0 km
	2.3 km	2.2 km	1.0 km
.04 g/cc (water saturation)	1.0 km	0.6 km	1.5 km maximum

We also modeled the geodetic strain to determine the volumetric strain within the depleted reservoir volume. At The Geysers, horizontal contraction and surface subsidence measured by Lofgren (1979) overlie the portion of the reservoir volume depleted by steam production, (Figure 3), as shown by pore pressure decay (Lippman and others, 1977).

By modeling the geodetic data, (assuming simple dilatation), we calculated strains up to 10^{-4} within the depleted reservoir volume. By assuming that the reservoir strain is a mechanical response to increased effective stress as the pore pressure decays, we also calculated a bulk or "framework" modulus for the reservoir matrix. The change in effective stress may be calculated from the pore pressure change (which is estimated from data presented by Lippman and others, 1977), and a value for the "intrinsic" bulk modulus of the reservoir rock (Rice and Cleary, 1976). For an intrinsic bulk modulus of the reservoir rock we used lab measurements of the compressional velocity of Franciscan graywacke (Stewart and Peselnick, 1978) combined with values of Poissons ratio form earthquake data (Majer and McEvilly, 1978). The strain we calculated for a given reservoir volume was then combined with the changes in effective stress to produce a value for the bulk modulus of the reservoir matrix. The bulk moduli determined in this way from the geodetic data are listed in Table 3 for several reservoir volumes (which were determined using the gravity and temperature measurements).

Bulk moduli obtained from microseismic monitoring within the reservoir (Majer and McEvilly, 1978) are an order of magnitude larger (bulk modulus about 3.X 10^5 bars), and lie between lab values calculated from Stewart and Peselnick (1978) and calculated bulk moduli for the reservoir matrix. The bulk moduli determined from seismic measurements therefore produce much smaller strains given the observed changes in pore pressure and calculated changes in effective stress.

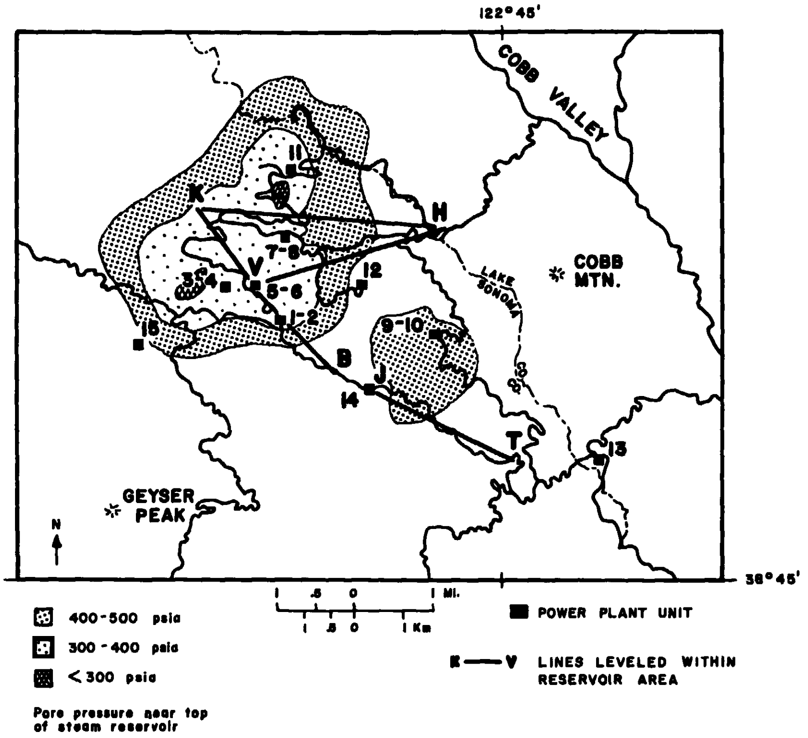


Figure 3. First order leveling lines in The Geysers steam field and the pore pressure decay near the top of the steam reservoir as of early 1977.

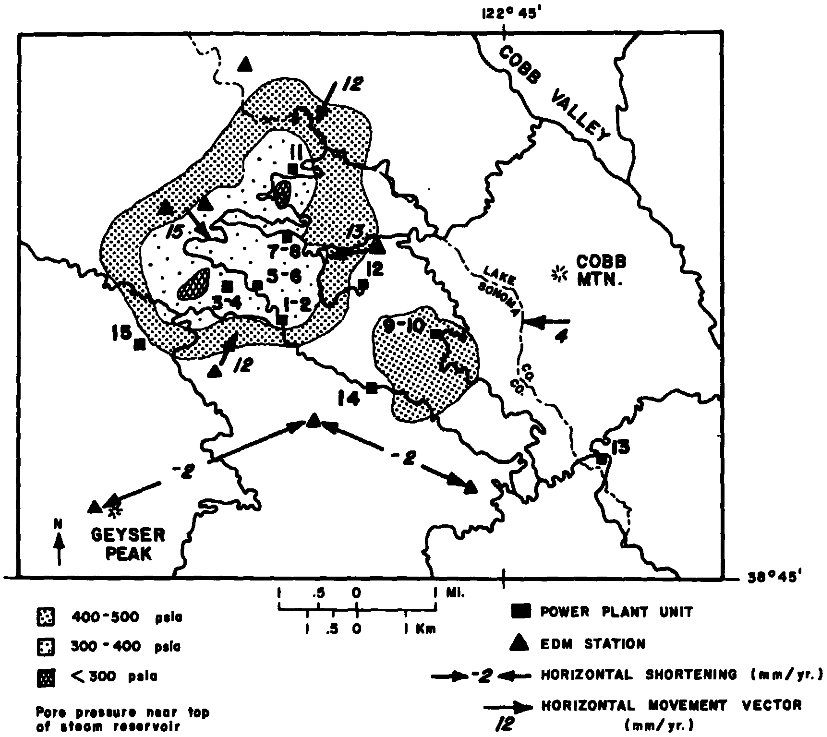


Figure 4. Horizontal movement vectors from high precision geodolite surveys (Lofgren, 1979) and the pore pressure decay near the top of the steam reservoir.

Thus the larger moduli measured at seismic frequencies (averaging about 10 Hz) requires a mechanical model for the reservoir in which there is a significant change of modulus with either frequency or strain amplitude. For seismic stress waves, the small stresses and strains (10^{-8}) are linearly related. But the larger reservoir strain (10^{-4}) may not be linearly related to the changes in effective stress resulting from fluid depletion. This would be especially true if the large strain amplitude resulted from slippage along the numerous fracture surfaces within The Geysers steam reservoir. This slip or creep may be one of the principal reasons our data appears to confirm the commonly observed discrepancy between static and dynamic moduli.

Non-mechanical, thermal contraction of the depleted reservoir volume is an alternative model of reservoir strain at The Geysers. Thermal contraction requires a temperature decline (which at the present is too small to measure) over the bulk reservoir volume, and which occurs independently of mechanical coupling between the pore fluid and the rock matrix. If 0.3% of the bulk reservoir volume is water which flashes to steam, this not only produces a mass deficit of -.003 g/cc, but also decreases the temperature of the reservoir by 1.5 degrees Celsius. Measurements of the thermal expansivity of various rock types (Skinner, 1966) imply that a reservoir strain of 8.X 10^{-5} would correspond to this temperature change, and the strain so obtained agrees with the values calculated from geodetic data (Table 3). Thus a change in liquid content of 0.3% of the bulk reservoir volume, with the inherent temperature change, fits the observed deformation data on The Geysers steam system.

Thus we have shown that two alternative strain mechanisms are consistent with the response of the steam reservoir to fluid depletion at The Geysers. Since both mechanisms are related to fluid withdrawal and pore pressure decay, there are at this time no measurements capable of distinguishing thermal from mechanical strain.

By monitoring the gravity and geodetic strain at The Geysers as the reservoir is depleted, the outward growth of the depletion zone may be studied in detail. Once the fluid is completely depleted in a section of the reservoir, then it

TABLE 3. RESULTS OF MODELING RESERVOIR STRAIN WITH PURE DILATATION.

SHAPE.	radius	height	volume	mass deficiency	strain ($\Delta V/V \times 10^{-5}$) d=0.5 km	strain ($\Delta V/V \times 10^{-5}$) d=1.0 km
CYLINDER	1.6 km	4.7 km	37. km^3	.002 g/cc	3.2 ± .3	6.0 ± .6
	1.5 km	3.5 km	25. km^3	.003 g/cc	4.7 ± .5	7.8 ± .8
	1.5 km	2.1 km	15. km^3	.005 g/cc	6.7 ± .7	10.2 ± 1.0

	radius	depth to center	volume	mass deficiency	strain ($\Delta V/V \times 10^{-5}$)
SPHERE	2.1 km	2.5 km	37. km^3	.002 g/cc	4.2 ± .4
	1.8 km	2.5 km	25. km^3	.003 g/cc	6.4 ± .6
	1.6 km	2.5 km	15. km^3	.005 g/cc	10.5 ± 1.0

POISSONS RATIO ASSUMED TO BE 0.25.

USING CYLINDER MODEL, EFFECTIVE BULK MODULUS FROM STRAIN DATA IS

$$K = 0.3 \text{ to } 0.5 \times 10^{5} \text{ bars.}$$

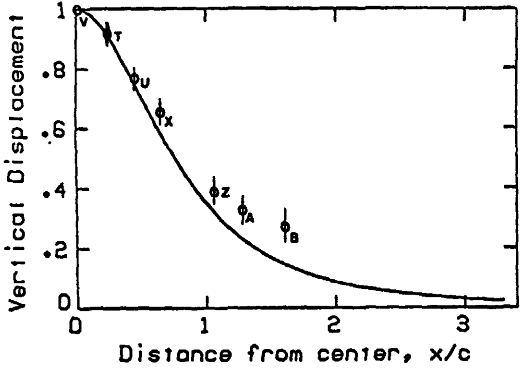
SEISMIC REFRACTION DATA (MAJER AND McEVILLY, 1978) IMPLY THAT THE BULK MODULUS IS

$$K_s = 2.5 \text{ to } 3.0 \times 10^5 \text{ bars.}$$

VALUES ABOVE ARE CALCULATED FOR THE PERIOD FROM 1973-75 DURING WHICH THE PORE PRESSURE CHANGE WAS BETWEEN ONE AND THREE BARS.

will be possible to estimatc the initial liquid saturation in that portion of the reservoir. If the liquid saturation in one section of the reservoir may be extrapolated to other parts of the steam reservoir, then since the rate of of mass depletion is known, a lifetime estimate may be made for The Geysers steam field.

Surface Strain due to a Sphere



Surface Strain due to a Cylinder

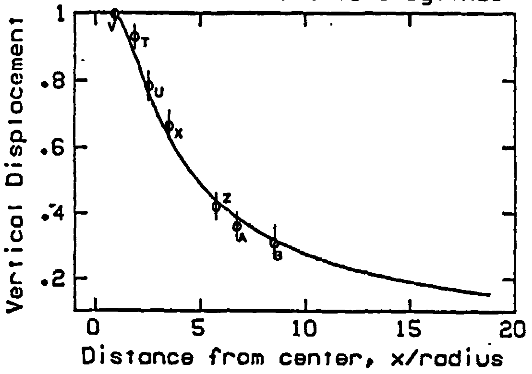


Figure 5. First order leveling data compared to theoretical vertical movement for both a cylinder and a sphere in an elastic half space. Radius of the cylinder is 1.5 km, and the depth to the center of the sphere is 2.5 km.

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